Renewable and Sustainable Energy Reviews 41 (2015) 68–84

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Solar water heating: From theory, application, marketing and research

Zhangyuan Wang [a,c,*], Wansheng Yang [a], Feng Qiu [a], Xiangmei Zhang [a], Xudong Zhao [b,a]

[a] School of Civil and Transportation Engineering, Guangdong University of Technology, Guangzhou, Guangdong 510006, China
[b] School of Engineering, University of Hull, Hull HU6 7RX, UK
[c] State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou 510640, China

ARTICLE INFO

Article history:
Received 7 November 2013
Received in revised form
20 July 2014
Accepted 12 August 2014

Keywords:
Solar water heating system
Global market
Mathematical analysis
Research questions
Production
Engineering application

ABSTRACT

The aim of the paper is to provide a comprehensive critical review towards the solar water heating (SWH) technology in terms of its theory, application, market potential and research questions. The theoretical issues relating to the solar water heating technology were illustrated in terms of the working principle, classification and associated mathematical expressions. The existing SWH production and engineering application were introduced and its future market potential was also predicted. Furthermore, research questions relating to the SWH were analysed involving (1) whole structure and individual components layout, sizing and optimisation; (2) thermal performance simulation and prediction; (3) laboratory based measurement compared against the modelling prediction; (4) dynamic performance evaluation through real time and on-site measurement; (5) energy saving, economic and environmental performance assessment, and social acceptance analyses; and (6) dissemination, marketing and exploitation strategies. Finally, the opportunities for the further works on the SWH were identified. This study will help understand the current status of the economic and technical developments, identify the barriers remaining to the existing solar water heating systems, develop the potential research areas to improve the performance of the systems, establish the associated strategic plans related to the design and installation of the system and promote the solar thermal global market. The study will contribute to achieving the China and international targets for energy saving, renewable energy utilisation, as well as carbon emission reduction in building sector.

Contents

* Corresponding author. Tel.: +86 20 3932 2515; fax: +86 20 3932 2511.
E-mail address: zwang@gdut.edu.cn (Z. Wang).

http://dx.doi.org/10.1016/j.rser.2014.08.026
1364-0321/

1. Introduction

Over the past few decades, global energy consumption has been steadily growing. In 2008, the total consumed primary energy reached a level of 11,315 million tonnes of equivalent oil (equalling to 474 EJ) [1], of which 80–90% was from the burning of fossil fuels. Despite the latest energy review [2] indicating that owing to the unexpected global financial crisis the world's primary energy consumption dropped by 1.1% in 2009, energy consumptions in some developing countries, particularly in Asia, were still rising. In addition, overexploitation of the primary energy sources has caused the depletion of fossil fuels, and there will only be 119 years of coal production, 46 years of oil production and 63 years of natural gas flow left in the ground with the current proved reserves [3]. The principle of energy supply and demand suggests that as fossil fuel supplies diminish, rising energy prices will impact on the development of the global economy.

On the other hand, the combustion of fossil fuels for energy, industrial processes and transportation has caused a significant increase in the emissions of greenhouse gases to the atmosphere. It has been agreed by most scientists that this growth is the primary cause of global warming. Over the last 30 years of the 20th century, global temperature has already risen 1.4 °C [4], and it will continue to rise over the next decades. This warming will cause significant changes in sea levels, ecosystems and weather events, which will threaten people's health and way of life, and cause irreversible losses to species of both plants and animals.

Thus, the inflation of energy prices and the impact of climate change have led to the exploration of alternative, renewable energy sources for the purposes of energy savings and environmental protection.

Solar thermal is one of the most cost-effective renewable energy technologies and has enormous market potential globally. Since the beginning of the 1990s, the world solar thermal market has been continuously developing. In Europe, the solar thermal market was tripled from 2002 to 2006 and is still booming [5]. The European Solar Thermal Industry Federation (ESTIF) has predicted that, by 2020, the European Union (EU) will reach a total operational solar thermal capacity of between 91 and 320 GW; and by 2050, the EU will eventually achieve 1200 GW of solar thermal capacity [6].

Solar water heating is one of the most popular solar thermal systems and accounts for 80% of the solar thermal market worldwide [7]. Over the past four decades, solar water heating systems have gained wide applications in the building sector globally [8]. In the meantime, the systems have been identified with a number of technical problems that have become the barriers to their promotions, e.g., low existing efficiency, high heat loss and poor solar energy harvesting capability. Some challenges also relate to their installations to the buildings and capital costs.

Most solar water heaters (SWH) for buildings are flat-plate types or conventional heat pipes array installed on roofs for layout convenience. This installation requires long runs of pipelines delivering water from the roof heaters to the outlet points and receiving water from the water mains. Thus, the cost of the system is high; most importantly, the installation detracts from the aesthetics of the building, particularly those multi-storey buildings containing a large number of end users.

In recent years, several façade-based solar heaters have been developed and used in practical projects [9–11]. These devices are simply positioned on the walls or balconies [12], which prevent the occupation of roof space and shorten the distance of piping runs, and thereby improve the building's aesthetic view. However, this layout still requires the transportation of water from the inside of the building to the outside, which may cause the hazard of pipes freezing during winter operation.

Further development has been undertaken to introduce the loop heat pipe concept into the solar collectors. Loop heat pipe [13,14] was a two-phase (liquid/vapor) heat transfer device allowing a high thermal flux to be transported over a distance of up to several tens of metres in a horizontal or vertical position owing to its capillary or gravitational structure. However, the starting-up problem of the loop heat pipe still exists influencing the operating stability of the solar collector, as well as the high initial cost of the system. Still, the loop-heat-pipe-based solar collectors are in the laboratory experimental stage that the structure of the system needs to be optimised.

Although many works have been undertaken with the solar thermal collectors, it seems to remain certain level of ambiguity

Nomenclature

A	area, m^2
C_p	specific heat capacity, J/(kg K)
F_R	collector heat removal factor
$F_R{}'$	exchanger heat removal factor
I	total solar radiation on the surface of the collector, W/m^2
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
Q	energy flux, W
t	time, s
T	temperature, °C
T_r	required temperature for room space or hot water, °C
$T_t{}'$	tank water temperature at the end of a time period, °C
U	heat loss coefficient, W/(m^2 K)
U_1	temperature-dependent heat loss coefficient, W/(m^2 K)
U_2	temperature-dependent heat loss coefficient, W/(m^2 K)
α	absorptivity
δ	thickness, m
ε	effectiveness
η	efficiency
η_0	optical efficiency
λ	thermal conductivity, W/(m K)
τ	transmittance

Subscripts

a	ambient
$back$	back of the collector
c	collector
d	symbol of differential coefficient
$edge$	edges of the collector
f	heat transfer fluid across the collector
i	inlet
l	heat loss
L	heat load
min	minimum values
o	outlet
s	secondary loop between the exchanger and storage
tk	hot water tank
top	top glass cover
u	useful energy
w	water

with this technology in several aspects: (1) type and classification; (2) advantages and disadvantages; (3) performance data and evaluation methods; (4) current status and future potential with the SWT application; (5) research problems and progress; and (5) opportunities for further development. To make up a clear sense regarding the SWTs, a comprehensive critical review is thought to be highly demanding and hence what we will address in this paper. This study will help understand the current status of the economic and technical developments, identify the barriers remaining to the existing solar systems, develop the potential research areas to improve the performance of the solar systems, establish the associated strategic plans related to the design and installation of the system and promote the solar thermal global market. The study will therefore contribute to achieving the China and international targets for energy saving, renewable energy utilisation, as well as carbon emission reduction in building sector.

2. Technical background of solar water heating systems

2.1. Working principle

A solar water heating system, as shown in Fig. 1 [7], consists of a discrete collector, which is designed to maximise solar absorption and reduce heat losses. The solar collector could be either a black-painted flat-plate absorber bonded to copper piping and covered with a transparent glass (flat-plate collector) or copper tubing surrounded with evacuated and selectively-coated glass tubes (evacuated-tube collector). When solar radiation passes through the transparent glass or evacuated tubes and impinges on the collector surface of high absorption, a large part of the energy is absorbed by the collector and then transferred to the fluid to be transported in the pipes. The heat transfer fluid, usually a mixture of water and antifreeze fluid, is either pumped (active system) or driven by natural convection (passive system) through the collector to a coil heat exchanger at the bottom of a cylinder tank (indirect system), where the heat it carried is further transported to the service water for storage or direct use. The tank contains an auxiliary heater, e.g., electric immersion heater or conventional boiler, for winter use and is insulated with polyurethane for hot water storing [15,16].

2.2. Classifications

2.2.1. Passive and active systems

Based on whether or not they require pumps to function, solar water heating systems could be grouped into two basic configurations, namely passive and active systems, as shown in Fig. 2(a) and (b) [17].

Passive systems transfer heat from the collector to the tank located above the collector by natural circulation, which could supply hot water at a temperature of 60 °C, and are the most commonly used solar water heaters for domestic applications [18]. **Active systems** use the electric pump, controller and valve to circulate water through the collector. This category of solar system uses electricity to accomplish the transfer of thermal energy by running the pump. A differential thermostat is normally used to control the circulation of the water, when the temperature of the water at the top header is higher than the temperature at the

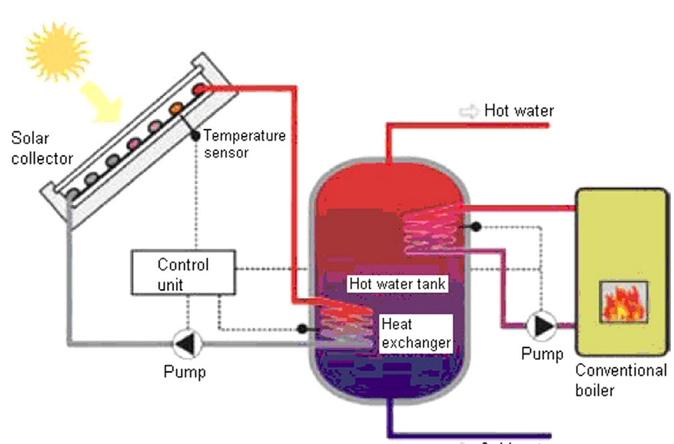

Fig. 1. Schematic of a conventional solar water heating system [7].

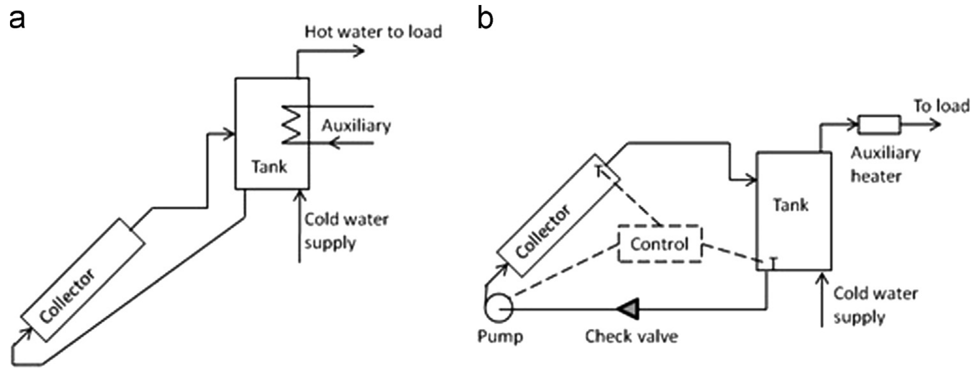

Fig. 2. Schematic of the passive and active solar water heating systems [17].

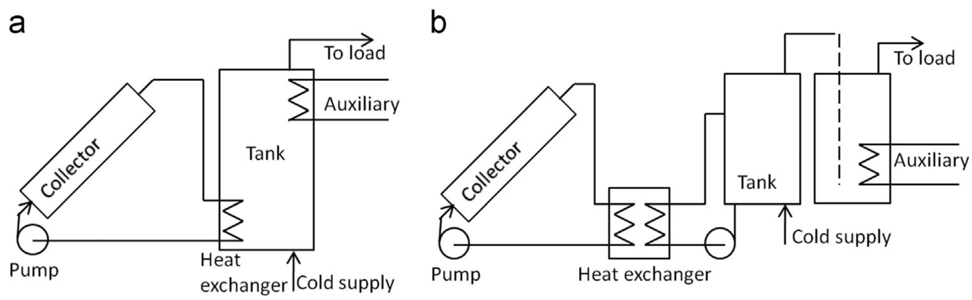

Fig. 3. Schematic of the indirect solar system with the exchanger inside or outside the tank [17].

bottom of the tank by a sufficient margin. A check valve may be required to prevent reverse water circulation [17].

Compared to the passive system, the efficiency of the active solar water heating system is one crucial advantage and is usually between 35% and 80% [19] over the passive system in the range of 30–50% [18]. Another advantage is that the collector in the active system does not need to be as close to the tank. Therefore, the active system can be used for multistory buildings. The main drawbacks of the active system are its complicated nature which is dependent on electricity and the requirement for experienced personnel to operate it, which will lead to a much higher running cost than for the passive system.

2.2.2. Direct and indirect systems

Based on whether or not they require a heat exchanger, solar water heating systems could be categorised into direct (Fig. 2 [17] above) and indirect systems (Fig. 3 [17]).

In a **direct system**, the service water is directly circulated between the water tank and the collector, while for an **indirect system**, a heat transfer fluid, usually antifreeze, distilled water or an organic fluid, is circulated through the solar collector. A heat exchanger is employed to affect the heat transfer from the collector to the service water in the tank. The heat exchanger could be used inside or outside the hot water tank as shown in Fig. 3 (a) and (b).

The indirect system in most situations performs better than the direct one, which is less climate-selective and more suitable for use in regions that experience cold temperatures.

2.2.3. Solar systems in different solar collector configurations

Solar collectors can have many variations according to their operating temperatures as shown in Fig. 4 [7], which summarises most of the possibilities. Unglazed panels and flat-plate water and air collectors are categorised into the low temperature solar collectors. Evacuated-tube, line-focus, and point-focus collectors are classified as high temperature solar collectors.

2.2.3.1. Low temperature solar collectors. **Unglazed panel** is most suitable for swimming pool heating. It is only necessary for the water temperature to rise by a few degrees above ambient air temperature.

Flat-plate water collector is the mainstay of domestic solar water heating worldwide. It is usually single glazing but may have an extra second glazing. The panel usually has a black surface or selective coating that has both high optical absorption and low emission to cut heat loss. An absorber plate has high thermal conductivity to be capable of transferring the collected energy to the water with a minimum temperature drop.

Flat-plate air collector is not as popular as a water collector and is mainly used for space heating. An application of this collector is in combination with a photovoltaic panel to produce both heat and electricity.

2.2.3.2. High temperature solar collectors. **Evacuated-tube collector** consists of a set of modular tubes, where convective heat losses are minimised by virtue of the vacuum in the tubes. The absorber plate is a metal strip in the centre of each tube, and a heat pipe is used to carry the collected energy to the water which circulates along a header at the top of the pipe array.

Line-focus collector could concentrate the sunlight onto a pipe running down the centre of a trough that could be pivoted to track the Sun up and down or east to west. It is mainly used for generating steam for electricity plants. A line-focus collector can be orientated with its axis in either a horizontal or vertical plane.

Point-focus collector is also used for steam generation or driving a Stirling engine, but needs to track the Sun in two dimensions.

2.2.3.3. Comparison of the evacuated-tube and flat-plate collectors. Flat-plate solar water heating systems have been used worldwide owing to their structural simplicity and the low cost of the flat-plate collector. However, evacuated-tube collector with heat pipes array is growing in popularity, as it has many advantages over the flat-plate

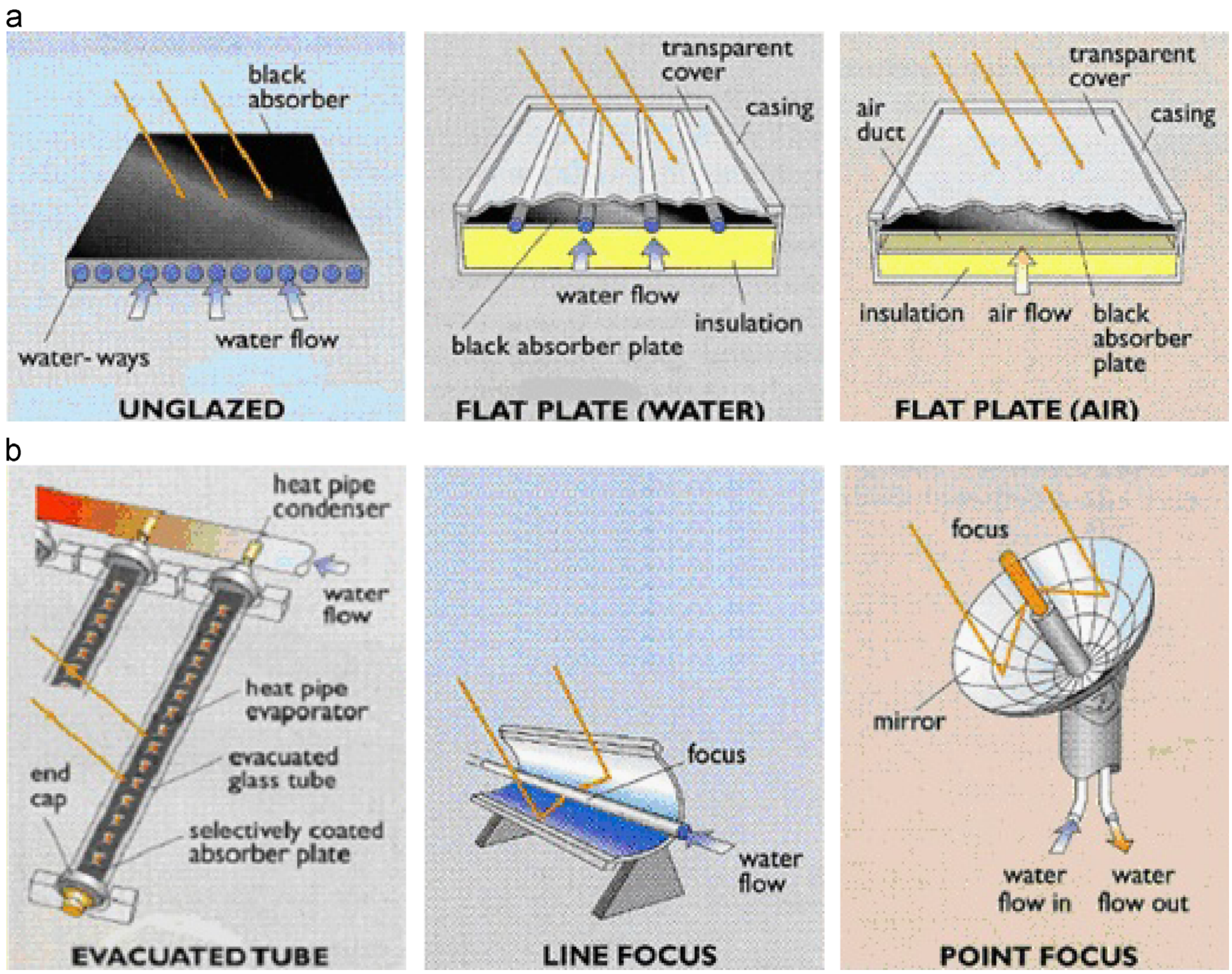

Fig. 4. Classification of solar collectors: (a) low temperature solar collectors and (b) high temperature solar collectors [7].

Table 1
Comparison of the evacuated-tube and flat-plate collectors.

	Evacuated-tube collector	Flat-plate collector
Heat production	Rapid – vacuum prevents heat losses	Slow
Heat losses during daytime	Negligible	High
Influence of the incidence angle of the sun rays	Maximum solar absorption throughout the day – cylindrical shape	Maximum solar absorption at noon – flat shape
Cold weather operation	Satisfactory performance – vaporising/condensing processes within the heat pipes	Limiting effect – direct heat transfer processes, risk of freezing
Maximum operating temperature range	Above 95 °C	Up to 80 °C
Cost-effective	Advanced technology at competitive price	Old technology at higher price
Hot water availability	For a greater number of days throughout the year – high efficiency	For a lesser number of days throughout the year
Position of the collector on the roof	Assembled onto the surface of the roof	Preassembled flush with the roof – lifting may be required

collector. The main features of the evacuated-tube and flat-plate collectors are compared in the following Table 1 [7,20].

2.3. Mathematical analysis

The performance of the solar water heating system will be influenced by the existence of the solar collector, heat exchanger or water tank, which will be separately described as

2.3.1. Energy balance of solar collector

For any solar thermal system, the overall energy balance of the solar collector at a steady state is shown in Fig. 5 and could be expressed as [21]

$$Q_u = Q_i - Q_l \tag{1}$$

The energy absorbed by the solar collector depends on the optical properties of the collector cover and absorber plate and can be estimated as [21]

$$Q_i = A_c I \tau \alpha \tag{2}$$

Part of Q_i will be released to the ambient. In the case of a flat-plate collector, the heat is normally assumed to release through the top, back and sides of the collector [21] as expressed in the following

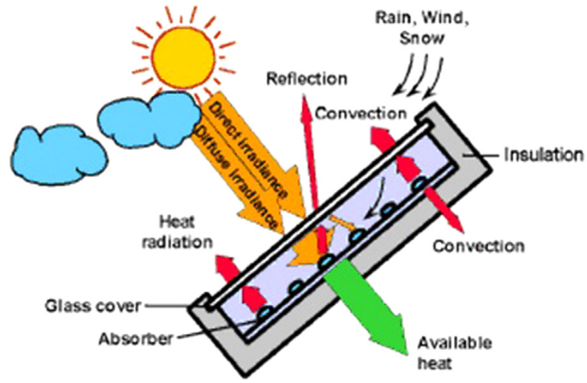

Fig. 5. Energy balance of a solar collector [21].

equation:

$$Q_l = Q_{l,top} + Q_{l,back} + Q_{l,edge} = A_c U_{l,top}(T_c - T_a) + A_c U_{l,back}(T_c - T_a) + A_c U_{l,edge}(T_c - T_a) = A_c(U_{l,top} + U_{l,back} + U_{l,edge})(T_c - T_a) = A_c U_l (T_c - T_a) \quad (3)$$

$$U_{l,edge} = \frac{\lambda_{edge}}{\delta_{edge}} \frac{A_{edge}}{A_c} \quad (4)$$

It should be noted that $U_{l,top}$ is a function of the number and properties of the glass cover as well as the ambient temperature, and $U_{l,back}$ is a function of the thickness and thermal conductivity of the insulation.

Thus, the useful energy delivered by the collector in an area of A_c could be expressed as

$$Q_u = A_c(I\tau\alpha - U_l(T_c - T_a)) \quad (5)$$

However, it is difficult to measure the mean plate temperature T_c. Therefore, Eq. (5) could be reformulated to calculate the useful energy delivered by the collector (Q_u) using the collector inlet fluid temperature (T_{fi}) by employing a collector heat removal factor (F_R) as in Eq. (6). The F_R is defined as the ratio of the heat delivered to the working fluid to the heat in the condition that the unified temperature of the collector plate equals the inlet fluid temperature. Since useful energy output is given by Eq. (7), F_R could be expressed as in Eq. (8). Eq. (6) is also known as the Hottel–Whillier–Bliss (HWB) equation [21].

$$Q_u = A_c F_R(I\tau\alpha - U_l(T_{fi} - T_a)) \quad (6)$$

$$Q_u = C_p \dot{m}(T_{fo} - T_{fi}) \quad (7)$$

$$F_R = \frac{C_p \dot{m}(T_{fo} - T_{fi})}{A_c(I\tau\alpha - U_l(T_{fi} - T_a))} \quad (8)$$

The collector efficiency (η) is the ratio of the useful energy delivered by the collector to the incident solar radiation on the collector during a specified period, which could be written as [21]

$$\eta = \frac{\int Q_u dt}{A_c \int I dt} \quad (9)$$

As the solar collector could be characterised using a number of design parameters, Eq. (9) could be simplified as

$$\eta = \frac{Q_u}{A_c I} = \frac{I\tau\alpha - U_l(T_c - T_a)}{I} = \tau\alpha - U_l\frac{T_c - T_a}{I} = F_R\tau\alpha - F_R U_l \frac{T_{fi} - T_a}{I} \quad (10)$$

It should be addressed that the variation of the collector efficiency with the operating temperature may be linear or nonlinear depending upon the characteristics of the collector. These can be represented as

$$\eta = \eta_0 - U_l \frac{T_c - T_a}{I}, \quad \text{for a linear relationship} \quad (11)$$

$$\eta = \eta_0 - U_{l1}\frac{T_c - T_a}{I} - U_{l2}\frac{(T_c - T_a)^2}{I}, \quad \text{for a nonlinear relationship} \quad (12)$$

The variations of the efficiency with the combined factor of $(T_c - T_a)/I$ for typical solar collectors including unglazed panels, glazed black absorbers, glazed selective absorbers and evacuated tubes are presented in Fig. 6 [7]. It is found that the efficiencies for all the collector configurations fall with the rise of the mean plate temperature and the decrease of the ambient temperature and solar radiation. The evacuated tubes are found to have stable efficiency in the range of 55–70%, while the efficiency of the unglazed panels drops considerably from 90% to 0% at low $(T_c - T_a)/I$.

2.3.2. *Reduction of the useful energy due to the employment of heat exchanger*

When a heat exchanger is fitted between the solar collector and storage point, the performance of the solar system will be affected by the effectiveness of the heat exchanger (ε). As shown in Fig. 7, ε is defined as the ratio of the actual heat exchange rate to the maximum possible heat exchange rate [7]

$$Q_u = \varepsilon(C_p\dot{m})_{min}(T_{fo} - T_{si}) \quad (13)$$

whereby, $(C_p\dot{m})_{min}$ is the minimum of $C_p\dot{m}_c$ and $C_{ps}\dot{m}_s$.

According to the Eqs. (6) and (7) in the solar collector analysis, the relationship between the useful energy (Q_u) and the collector outlet fluid temperature (T_{fo}) could be established as

$$Q_u = A_c F_R\left(I\tau\alpha - U_l\left(T_{fo} - \frac{Q_u}{C_{pc}\dot{m}_c} - T_a\right)\right) \quad (14)$$

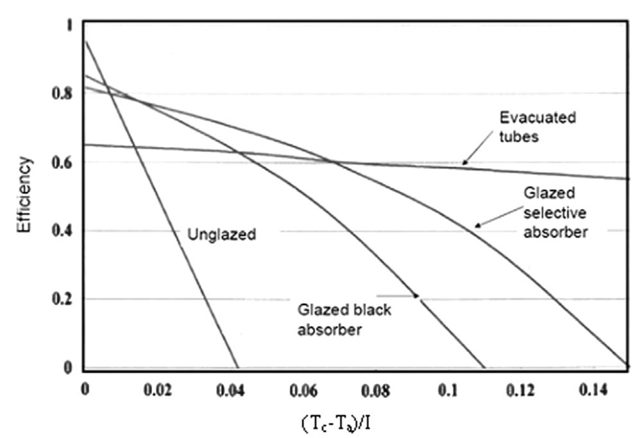

Fig. 6. Variations of the efficiency with the combined factor of $(T_c - T_a)/I$ for typical solar collectors [7].

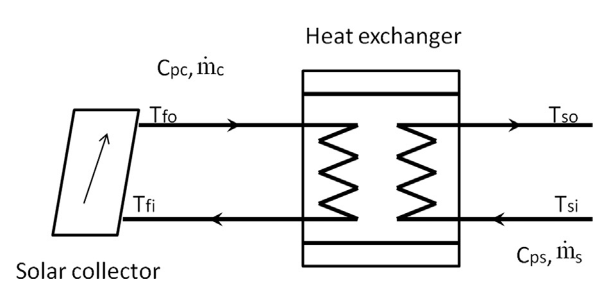

Fig. 7. Energy balance of the heat exchanger and its associated design parameters [7].

Then T_{si} from Eq. (13) will substitute T_{fo} in Eq. (14). Thus, the useful energy delivered to the tank could be expressed by using an exchanger heat removal factor ($F_{R'}$).

$$Q_u = A_c F'_R (I\tau\alpha - U_l(T_{si} - T_a)) \tag{15}$$

$$F'_R = \frac{F_R}{\frac{A_c F_R U_l}{C_{pc}\dot{m}_c}\left(\frac{C_{pc}\dot{m}_c}{\varepsilon (C_p \dot{m})_{\min}} - 1\right) + 1} \tag{16}$$

This indicates the reduction in heat output due to the existence of the heat exchanger. In other words, the ratio of F_R/F_R' represents the increase in the collector area required by the system with a heat exchanger, in order to achieve the same energy output as the system without the exchanger.

2.3.3. Energy balance of water storage

Considering the water in the tank is fully mixed with a unified temperature, the internal energy change rate of the tank could be expressed as [22]

$$C_{ptk} m_{tk} \frac{dT_{tk}}{dt} = Q_u - Q_L - Q_{l,tk} \tag{17}$$

Q_L is the heat load that is determined from the applications of the solar systems.

$$\text{For space heating,} \quad Q_L = UA_L(T_r - T_a) \tag{18}$$

$$\text{For water heating,} \quad Q_L = C_p \dot{m}_w (T_r - T_w) \tag{19}$$

$Q_{l,tk}$ is the heat loss from the tank, which is written as

$$Q_{l,tk} = UA_{tk}(T_{tk} - T_a) \tag{20}$$

It should be noted that the heat losses from the water pipelines of the distribution system can also be added.

If the water in the tank is not fully mixed, i.e., stratified (in the case of a passive system), the tank could be modelled by dividing the water into layers and establishing energy balance equations for each layer [22].

As a result, the tank water temperature for a solar system having the collector, tank and load can be estimated by integrating Eq. (17) as

$$T'_{tk} = T_{tk} + \frac{dt}{C_{ptk} m_{tk}} (Q_u - Q_L - Q_{l,tk}) \tag{21}$$

For an initial value of T_{tk}, the water temperature at the end of dt can be calculated by using Eq. (21).

Thus, the entire day's useful energy, tank water temperature, load demand and contribution of the solar energy in meeting that demand can be obtained from various design parameters, e.g., collector area, tank capacity and time when auxiliary energy is needed [23].

2.4. Factors influencing the performance of solar water heating system

The performance of the solar water heating system is dependent upon a number of factors which can fall into broad categories such as climate, system design and installation as well as user interactions.

Local climatic conditions can play a significant role in determining the proper orientation and tilt angle for the collectors, since the amount of solar insolation incident at any one spot on the Earth's surface varies throughout the year [24].

The design parameters of the system, e.g., collector area, fluid type, collector mass flow rate, storage tank volume and height, heat exchanger effectiveness, size and length of connecting pipes, absorber plate material and thickness, number and size of the riser tubes, tube spacing, and collector's aspect ratio, should be taken into account when designing, planning and building the solar system [25]. The building's roof orientation and slope, shading factors, perceived aesthetics, and local covenants also play significant roles in the installation of the solar system [24].

Solar energy systems require periodic inspections and routine maintenance to keep them operating efficiently. The components may need repair or replacement to prevent scaling, corrosion, and freezing, requiring the interaction with engineers, manufacturers and clients. Increased user acceptance of solar designs and technologies will accelerate the market penetration. The overall benefit will be an increased use of solar energy in buildings, thus reducing the non-renewable energy demand and greenhouse gas emissions [26].

3. Global solar thermal market

3.1. Current status and the global market potential for solar thermal

Solar energy is one of the primary energy sources, with 120,000 TW striking the Earth's surface excluding those reflected by the atmosphere directly to the outer space. Compared to the total primary energy supply of 433 EJ in 2002 equivalent to 13.75 TW of power consumption [27], solar energy exceeds 8700 times the primary energy supply, meaning that the energy the Earth received from the Sun each hour is as much as humankind consumed in one year.

Heating consumes the largest share of primary energy supply and accounts for 40–50% of world energy demand, including cooking and high temperature industrial processes. The building sector consumes 35% of the final energy demand, of which 75% is for space and domestic water heating. In Europe, the final energy demand for heating (48%) is higher than for electricity (20%) or transport (32%) [27]. However, most of the heat supply currently comes from fossil fuels, indicating that there would be a significant market potential for replacement of these by renewable energy heating technologies.

Solar thermal designates all technologies that collect solar rays and convert the solar energy to usable heat for use in water, space heating and cooling, electricity, fuels and agricultural and industrial processes.

Over the last two decades, the global solar thermal market has increased significantly. Between 2000 and 2009, the global market of glazed solar collectors grew at an average rate of 20.8% as shown in Fig. 8 [28]. The annual installed capacity of glazed water collectors almost tripled between 2004 and 2009 worldwide, although it experienced a slight decrease of about 15% in 2007 [29]. China is the leader in the annual installed capacity as the largest solar thermal market globally with a sustained growth of 22%. It is recognised that the dominance of China is driven by its large population and the rapid growth of the solar heating sector. As the second largest market for glazed collectors, Europe showed an average annual growth rate of 20% [29], although a disappointing result (−9.9%) happened in 2009 due to a downturn of 23.1% in the largest European market, Germany. The US market, mostly of unglazed collectors, also dropped by 8.5% owing to the economic recession in 2009. Regardless of the above downturns, the Chinese (35.5%) and Australian (78.5%) markets were responsible for a global expansion of 27.3% in 2009 [28].

By the end of 2009, the total capacity of the solar thermal collectors in operation equalled 172.4 GW worldwide, of which 58.9% (101 GW) was in China. An overview of the different types of collectors applied in the leading countries in 2009 in respect of the total installed solar thermal capacity is shown in Fig. 9 [28]. China was the world leader in total solar thermal capacity, focusing on evacuated-tube collectors for the purposes of preparing hot water

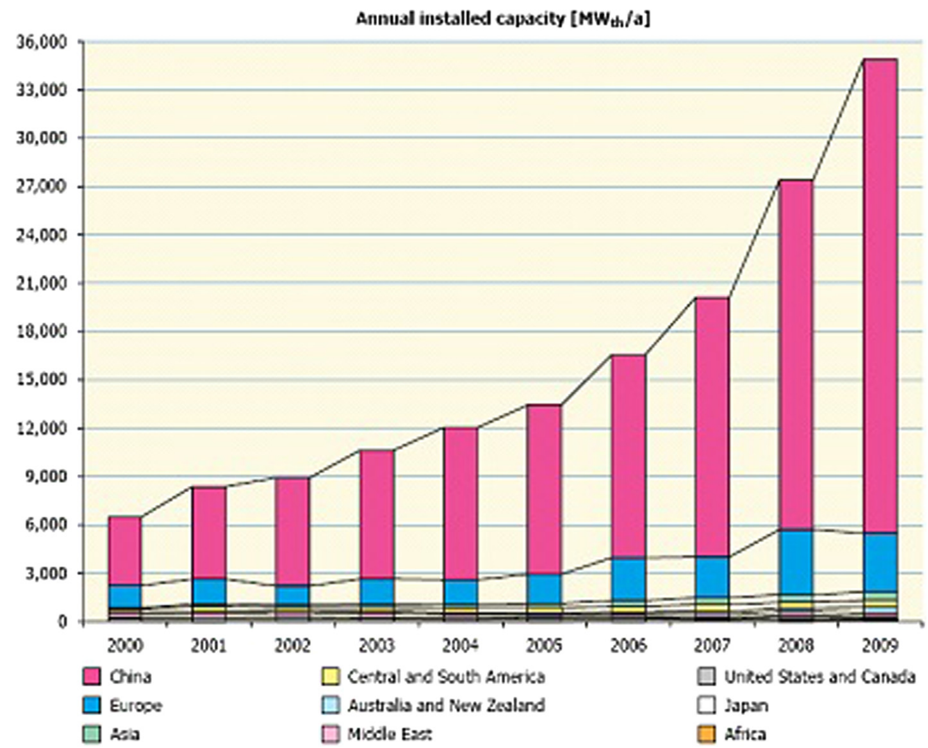

Fig. 8. Annual installed capacity of glazed water collectors from 2000 to 2009 [28].

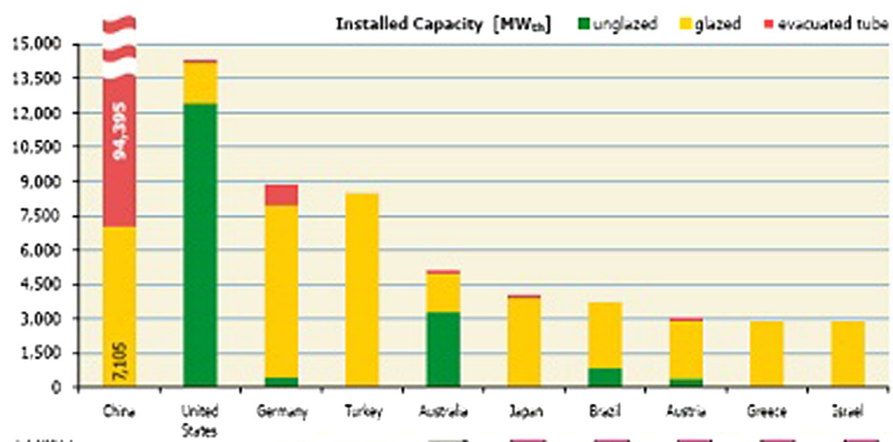

Fig. 9. Total installed capacity of water-based collectors by the end of 2009 [28].

and providing space heating. The United States (14.4 GW) ranked second owing to its high installation of unglazed collectors for swimming pool heating. With approximately 9 GW, Germany was holding third place, followed by Turkey, Australia, Japan, Brazil, Austria, Greece and Israel.

The energy production of all water-based solar thermal systems in 2009 was 142 TWh, corresponding to 14.4 million tonnes of oil equivalent (Mtoe). Provisional numbers for 2010 suggested that 2010 witnessed a 162 TWh energy production with 23.6 GW newly installed solar thermal collectors. Compared with other forms of renewable energy sources, solar thermal energy was second to wind power, excluding biomass and hydropower (Fig. 10 [28]). Still, it represented less than 0.5% of the global final energy demand [30].

The IEA World Energy Outlook 2008 [30] has foreseen a contribution from solar thermal of 45 Mtoe to the final energy demand for domestic water and space heating by 2030, thus leading to a 0.6% of the total final energy demand, if current energy policies continue. It has also anticipated that if all the policies currently under consideration are implemented by 2030, solar thermal will provide 64 Mtoe to the global energy demand, 10 times greater than the 6.6 Mtoe in 2003. China, Europe and the United States will still be the leading markets in the total installed solar thermal capacity in 2030, according to the projected figures [31].

The European Solar Thermal Industry Federation (ESTIF) [32] has forecast that, under full R&D and policy scenarios, a total installed capacity of 1019 GW in the EU will contribute about 15% of the low temperature heat demand by 2030. By 2050, the total capacity could reach 2716 GW to provide about 129 Mtoe of solar heat, which is roughly 47% of the overall heat demand in the EU.

3.2. *Driving forces to the expansion of solar thermal market*

The fast-growing global solar thermal market could be driven by several factors, such as low costs (under certain circumstances), financial incentives, regulatory instruments, education and other factors such as environmental and local visual impacts.

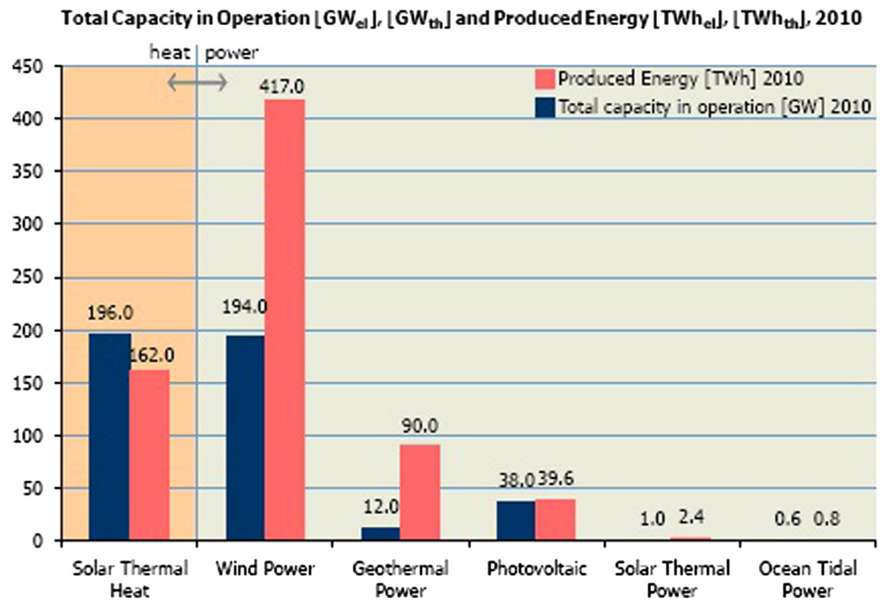

Fig. 10. Energy production of solar thermal in 2010 [28].

3.2.1. Solar heating cost

Compared to the energy prices for heat supplied by gas, fuel oil and electricity, solar thermal heating can be cost-effective under certain conditions ranging between £7 and £200 per GJ [31]. Solar heating costs vary considerably with weather conditions, the complexity of solar thermal installation, the application of solar thermal system for water heating only or for combined hot water preparation and space heating, and other factors such as the costs of labour and materials [27,31,33].

3.2.2. Financial incentives

Financial incentive is used to encourage energy customers to utilise renewable energy sources to meet heat demands, and aims to fill the cost gaps between the renewable energy sources and conventional energy technologies used for heating. The incentive schemes could be categorised into financial and fiscal [31,34]. Financial incentive is direct financial support funded from government budgets, which includes capital grant (subsidy), operating grant and soft loan. Fiscal incentive includes tax credits, reductions and accelerated depreciation, based on investment cost or energy production.

In many countries, capital subsidies for solar hot water have become common strategies. More than 20 countries provide capital grants, Value Added Tax (VAT) exemptions or tax credits for solar water heating investments including Austria, Germany, Greece, Japan, Netherlands, Spain, United Kingdom and United States. Capital grant or tax credit is typically 20–40% of a system's cost. The United States provides a 30% federal tax credit, in addition to many State-level rebates. Some companies also offer capital subsidies such as ESKOM in South Africa [35].

3.2.3. Regulatory instruments

Governments could intervene in the market by means of regulation, which forces the deployment of renewable energy heating by directly requiring the development of technologies. The regulatory instruments could be categorised into building regulations and standards [31].

Mandates for solar hot water in constructions have maintained a growing trend at both national and local levels [31,35]. Israel, for a long period of 30 years, was the only country with a national-level mandate. Spain required owners of all new and renovated buildings to provide 30–70% of domestic hot water demand by solar thermal energy. India's national energy conservation codes require atleast 20% of water heating capacity from solar for residential buildings, hotels and hospitals with central hot water systems. Hawaii became the first US state to mandate solar hot water in new single-family houses in 2009. Cities working on solar hot water policies, including Rome in Italy, would require 30–50% of hot water energy from solar for new buildings.

3.2.4. Education

Education to promote renewable energy heating aims to raise public awareness through information campaigns and training programmes. It may take the forms of technical assistance, financial advice, labelling of appliances and information distribution. For example, Canada's Office of Energy Efficiency has provided the free-downloadable, web-based RETScreen tool and numerous free publications on energy efficiency and renewable energy [31]. Training programmes may be established in schools, universities or among professional groups, such as the Certificated Solar Heat Installer and Planner run by experts within the Austrian solar industry [31].

3.2.5. Other factors such as environmental and local visual impacts

The concerns around saving energy and reducing carbon emission could also drive the fast-growing solar thermal market. Solar thermal requires no fossil fuels, thus producing little environmental pollution during its manufacturing, operation and decommissioning. Carbon emission from solar thermal energy is, therefore, small. If the external costs of energy technologies (e.g., environmental taxes and carbon emission charges) were taken into account, solar thermal energy could be cost-competitive with most heating technologies [31].

Solar thermal markets could also be driven by local visual impact. Recent solar systems are placed onto building roofs, and are more integrated into roof systems and building envelopes.

3.3. Existing barriers to the diffusion of solar thermal market

Although solar thermal has a broad market prospect, there are still various barriers to its diffusion, which can be grouped into three categories, i.e., technical barriers, economic barriers and other barriers including legal, educational and behavioural barriers.

3.3.1. Technical barriers

Over decades of development, many technical barriers have been identified, such as the nonexistence of a universal certification approach to specify the standards for production and utilisation, high heat losses at night, insufficient information on technical capabilities and lack of trained and competent installers. Recent problems focused on the availability of space for installation of solar thermal collectors, thermal storage with high energy density, availability of appropriate materials for mass productions of collectors, integration of solar equipment as part of the building's fabric and protection of solar collectors from freezing in cold weather [27,32]. Another barrier relating to the utilisation of solar energy is that the solar radiation reaching the Earth is intermittent, weather-dependent, highly dispersed, and unequally distributed over the surface of the Earth in that most of the energy is between 30ºN and 30ºS [27,36].

3.3.2. Economic barriers

Several economic barriers have impacted on the desire for increased utilisation of solar thermal in developing countries, including lack of public awareness, lack of energy policies, low levels of income, lack of subsidies, short-term investing syndrome and lack of institutional support. For developed countries, the principal economic barriers are capital cost, poor regulation of promotion and poor public perceptions [27]. Solar heating cost is another significant economic barrier; although it is cheaper than the electricity price in Denmark and roughly the electricity price in Austria, Germany, Italy, the Netherlands and Japan, it is more expensive than the heat from natural gas in urban areas [37]. Finally, customers, especially the less wealthy, may only consider investments with immediate returns, since the benefits due to low running costs may not always offset the large capital expense [27].

3.3.3. Other barriers such as legal, educational and behavioural barriers

The largest barrier in this category is that property developers and building owners have little incentive to invest in energy-saving equipment in new constructions and rental markets. This is because the returns on investments will directly flow to the actual occupants rather than to them [27]. Another barrier existing in collective dwellings or multi-storey buildings is that the installation of a single device may become technically complex, and will require permits from a majority of co-owners [27]. The diversity of local requirements is another barrier as solar systems need to be considered in terms of their compatibility with existing community aesthetic standards and architectural requirements [27,38]. Finally, some barriers relate to behaviour including reluctance to manage a complex system, solar intermittence leading to low comfort levels for either space or water heating, and changes in habits [27].

3.4. Applications of solar water heating systems in buildings – examples

Since the 1960s, flat-plate collectors supported by metal frames have been mounted on the flat rooftops of buildings as shown in Fig. 11 [39]. In recent years, roof-mounted solar collectors have been widely installed in single-family houses or multi-family buildings across different countries with different climates from cold to temperate, such as Netherlands, Germany and Switzerland. The 23 m^2 roof-mounted solar collector in the configuration of evacuated tubes to support the central heating system for domestic hot water in Germany was illustrated in Fig. 12 [40], which helped reduce the heating consumption by 90% compared to the conventionally constructed buildings. However, both flat-plate and evacuated-tube installations occupy a large roof space, leading to deterioration of the building's aesthetic view.

Fig. 11. Brandaris Building with 760 m^2 roof-mounted flat-plate collectors in the Netherlands in 1968 [39].

Fig. 12. ISIS Demonstration Building with 23 m^2 roof-mounted evacuated tubes in Germany in 2002 [40].

Fig. 13. House W with 8.4 m^2 roof-integrated flat-plate collectors in Czech Republic in 2003 [41].

In order to improve the architectural appearance of the building, a roof-integrated solar water heating system has been proposed, which replaces the finishing layer of the roof insulation as shown in Fig. 13 [41]. However, this system has proven to be less efficient than the roof-mounted solar system owing to the fixed tilt angle of the collector, particularly during cold weather.

For both roof-mounted and roof-integrated solar water heating systems, the water will be transported over a long distance from the exterior building roof to the interior tank, and then flow back to the outside. This method will either consume a large amount of

electricity to run a pump (active system) or result in low solar conversion efficiency by virtue of the natural circulation (passive system). This will lead to increased system electrical usage and operating costs, high heat loss during transportation and reduction of the building's aesthetic quality. Most importantly, freezing problems may occur, particularly for multi-storey buildings with a large number of occupants.

In order to solve the problems mentioned above, building balcony/façade integrated solar water heaters have been brought into use in many practical projects as shown in Figs. 14 [42] and 15 [43]. This category of system could shorten the water piping distance, improve the occupants' living conditions, reduce the construction costs and enhance the building's appearance, owing to the joint use of the building and solar system components or replacement of the conventional building wall by the solar system [44].

Although a building balcony/façade integrated solar system is preferred over a roof-mounted or roof-integrated solar water heating system, it still has long pipelines transporting water between the exterior building wall and interior storage, which will ultimately affect the capability of heat transfer and lower the efficiency of solar conversion. In addition, this solar system still faces the problem of freezing during cold weather conditions, which is considered to be the biggest problem among the existing solar systems.

Most recently, the New Energy Centre (NEC) in National Taiwan University [45] developed a new solar water heater, which employed a loop heat pipe (LHP) system attached to the back of a thermosiphon tube and used to transfer the heat from the tube to the water tank as shown in Fig. 16. LHP is a two-phase (liquid/vapour) heat transfer device allowing a high thermal flux to be transported over a distance of up to several tens of metres in a horizontal or vertical position owing to its capillary or gravitational structure. It has a separate evaporator and condenser eliminating an entrainment effect occurring in between, and could operate under different gravitational regimes regardless of whether the evaporator is above or below the condenser [13,14,46]. This

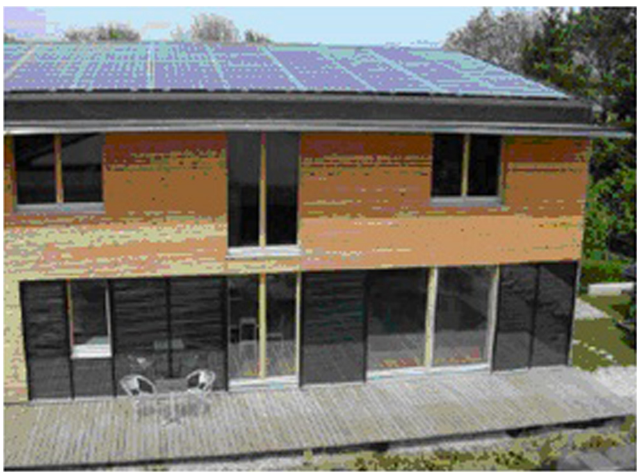

Fig. 14. Plus Energy House with 17 m^2 façade-integrated flat-plate collectors in Austria in 2001 [42].

Fig. 15. Sunny Woods with 6 m^2 balcony-integrated evacuated-tube collectors in Switzerland in 2001 [43].

Fig. 17. The experimental assembly: (a) CLOHP/CV circular tube solar collector; (b) adiabatic gap; (c) condenser water tank; (d) water storage tank; and (e) water pump [47].

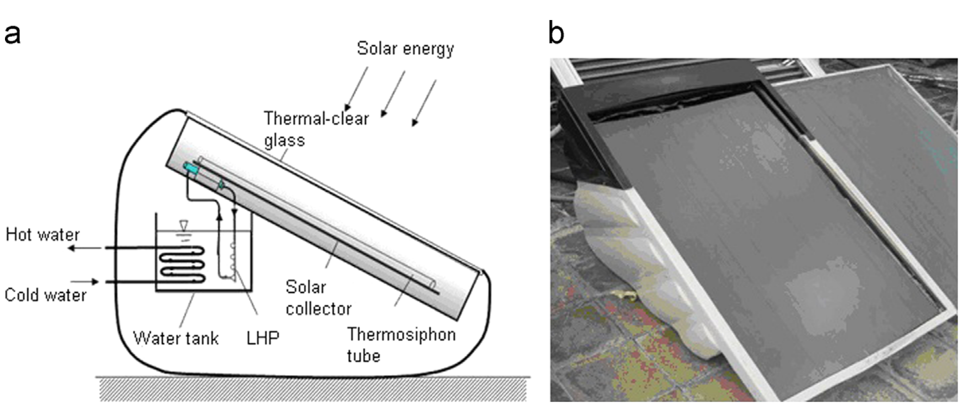

Fig. 16. LHP solar water heating system developed by NEC [45].

system with efficiency of 50.3% could be directly mounted on the rooftop of a building due to its structural integrity.

The circular glass tube solar collector with a set of closed-loop oscillating heat-pipes with check valves (CLOHP/CV) was described as in Fig. 17 [47]. An efficiency of approximately 76% was achieved, which correlated with the efficiency of the conventional evacuated tube system. The CLOHP/CV system offered the additional benefits of corrosion-free operation and absence of freezing during winter months.

4. Research questions – current status and deficiency

4.1. Overview of the solar water heating technology

Since the first solar water heating system was developed, extensive studies on its theoretical investigations, practical applications and demonstration tests have been conducted. Although the technology has become technically and economically mature, solar water heating technology continues to be a crucial area of research. Numerous researches covering various aspects of the technology, e.g., (1) integrated structure and individual components layout, sizing and optimisation, (2) thermal performance simulation and prediction, (3) laboratory based measurement compared against the modelling prediction, (4) dynamic performance evaluation through real time and onsite measurement, (5) energy saving, economic and environmental performance assessment and social acceptance analyses, and (6) dissemination, marketing and exploitation strategies, have been developed.

The experimental and theoretical study to determine the performance of phase-change energy storage materials for solar water-heating systems was conducted by Kaygusuz [48]. The variation of the outlet fluid temperature with different values of number of transfer unit and the variation of the stored energy with time for a phase change material ($CaC_{12} \cdot 6H_2O$) were investigated.

The improved low-cost large solar heating system design suitable for applications in mild sunny climates was proposed by Tsilingiris [49], where the prospects for the promotion of solar heating technology were favourable. The theoretical analysis was developed which allowed design and operational behaviour predictions of the physical system. Long-term efficiency and typical input-output performance was investigated based on statistically processed long-term meteorological measurements for Athens, Greece. Derived results indicated that substantial performance would be expected for the proposed fractional cost system design.

The solar water heating system with other domestic water heating systems, e.g., LPG and kerosene, used in Jordan was compared by Mohsen and Akash [50] in terms of benefits and costs using the analytic hierarchy process. In terms of cost, the solar system was the least expensive of 13% compared to the most expensive heating system, LPG, of 28%. In terms of benefits, the solar system was the most beneficial of 31%, while the least benefit was obtained from the kerosene water heating system of 9%. By considering cost-to-benefit ratio, solar was the least expensive of 7% with kerosene being the most expensive of 30%.

The characteristics of horizontal mantle heat exchangers for application in thermosyphon solar water heaters was theoretically and experimentally investigated by Morrison et al. [51]. The results indicated that configurations of mantle heat exchangers used in current solar water heater applications degraded thermal stratification in the inner tank.

The useful energy and temperature rise in the stored water of solar domestic water heating systems was analysed by Kalogirou et al. [52] using artificial neural network with the minimum input data based on 30 cases. Prediction errors within 7.1% and 9.7% were obtained.

The long-term performance of thermosiphonic type solar domestic water heating systems was predicted by Kalogirou and Panteliou [53] using an artificial neural network method that 30 systems have been tested and modelled according to the procedures outlined in the standard ISO 9459-2 at three locations in Greece. From these, data from 27 of the systems were used for training and testing the network while data from the remaining three were used for validation. Results indicated that the proposed method can successfully be used for the prediction of the solar energy output of the system.

The cost benefit analysis for evaluating solar water heating systems in comparison with competitive conventional technologies in Greece was presented by Diakoulaki et al. [54], as well as energy saving, environmental impact and job creation influences. The results showed that in the Greek conditions, the use of solar collectors resulted in considerable net social benefits if substituted for electricity and Diesel but not for replacing natural gas.

The multi-tank liquid-water system for storing low-temperature solar-derived heat was experimentally and analytically compared with a single-tank system by Mather et al. [55] due to the perceived economic advantage of the proposed system over the single-tank system in solar heating systems where the required total volume of water was rather large, e.g., 2000 l.

According to the minimum annual backup energy supplied to the system to meet an annual load, the design approach by using one absorber plate and a smaller and better insulated tank to maximise solar contribution and minimise material usage in the construction of solar water heating system was described by Mills and Morrison [56]. Two new designs were shown which allowed the solar fraction of systems to be increased to approximately 80–90% in Sydney, Australia using a standard model of domestic hot water usage specified in Australian Standard AS4234. Pollution from fuel use dropped to as little as 40% of that of conventional flat plate solar water heaters.

The influences of two glasses to the efficiency of a solar collector and the thermal performance of solar heating systems were measured by Furbo and Shah [57], one with antireflection surfaces by the company SunArc A/S and another without the antireflection layer. The transmittance of the glass was increased by 5–9% due to the antireflection surfaces, leading to an increased 4–6% of the collector efficiency, depending on the incidence angle of 8^{o}.

The yearly demand on solar water heating systems by the household sector was forecast, and the potential energy savings was computed by Kablan [58] during the period of 2001–2005. It was found that the net energy collected over the period was about 1454.4 million kWh, and the capital savings was estimated to be 46.28 million dollars, if the solar systems were used to heat water instead of the commonly used LPG gas cookers.

The realistic behaviour and efficiency of solar heating systems was analysed by Thür et al. [59] based on the comparisons of measured and calculated fuel consumptions of a boiler. The result showed that the potential of fuel reduction can be much higher than the solar gain of the solar thermal system. For some conditions the fuel reduction can be up to the double of the solar gain due to a strong increase of the system efficiency.

The methodology for potential estimation (technical, economic and market potential) of solar water heating in a target area of India with an area of 2 sq.km and population of 10,000 was proposed by Pillai and Banerjee [60]. This methodology linked the micro-level factors and macro-level market effects affecting the diffusion or adoption of solar water heating systems. The estimated technical potential and market potential are 1700 m^2 and 350 m^2 of collector area, respectively. The annual energy savings for the technical potential in the area is estimated at 110 kWh/capita and 0.55 million kWh/sq.km, with an annual

average peak saving of 1 MW, accounting for approximately 3% of the total electricity consumption.

The year-round thermal performance of active and passive solar water heating systems was studied by Lee and Sharma [61] from April 2003 to March 2004 in South Korea by using a 50/50 ratio of ethylene–glycol–water as a heat transfer fluid. Thermal efficiency for the system and collection efficiency for the collectors were calculated during the experiments.

Different models, i.e., semi-physical, state-space and, a combination of semi-physical and a feedforward neural network with one hidden layer and eight neurons, were explored by Sanino and Reischel [62] for a solar domestic water heating system located near Chile. The best models found, according to prediction accuracy, were of semi-physical nature, and final models were validated with classical statistical tests such as AIC and correlation analysis.

The methodology for synthesis, analysis, and optimisation of solar water heating systems was proposed by Kulkarni et al. [63] by identifying the minimum and maximum collector area and storage volume of solar water heating system for a given solar fraction. Based on the identified figures, the solar water heating system was optimised by minimising annual life cycle cost.

The simple and inexpensive test method to determine the thermal behaviour of solar domestic water heating system was proposed by García-Valladares [64]. The tests were carried out independently of the configuration between the solar collector and the storage tank, the way the fluid circulates and the type of thermal exchange.

The Clean Development Mechanism (CDM) potential of solar water heating systems was estimated in India by Purohit and Michaelowa [65]. The annual Certified Emission Reductions (CERs) potential of the systems in India was theoretically found to reach 27 million tonnes. Under more realistic assumptions about diffusion of the systems based on past experiences with the government-run programs, annual CER volumes by 2012 could reach 4–9 million and 15–22 million tonnes by 2020.

The revised solar water heating subsidy programme implemented through the Energy Efficiency and Conservation Authority (EECA) announced in November 2006 in New Zealand was described, and the international policies to determine the factors in gaining an increased penetration of solar systems for water heating was reviewed by Roulleau and Lloyd [66].

The simplified procedure of sizing of the solar installation of an individual dwelling was described by Raffenel et al. [67] by requiring only a small quantity of data and computing in a short time comparing with a more complex sizing method based on detailed simulation. The building and the solar installation had been modelled with the software TRNSYS 16 and their behaviour was simulated during a whole year. The results obtained from the complex sizing method were close to the ones expected by the simplified sizing procedure.

The indirect forced circulation solar water heating systems using a flat-plate collector for domestic hot water requirements of a single-family residential unit in Montreal, Canada was modelled by Hobbi and Siddiqui [25]. The design parameters of the system, e.g., collector area, fluid type, collector mass flow rate, storage tank volume and height, heat exchanger effectiveness, size and length of connecting pipes, absorber plate material and thickness, number and size of the riser tubes, tube spacing, and the collector's aspect ratio, were studied and optimised using TRNSYS simulation programme. The results showed that by utilising solar energy, the designed system could provide 83–97% and 30–62% of the hot water demands in summer and winter, respectively.

The effect of water replenishment on the system sizing was studied, and a novel strategy for water replenishment to improve the design and performance of solar water heating systems was proposed by Kulkarni [68]. For the cost-optimal system configuration, a reduction of 12.7% in the collector area and 10.2% reduction in the storage volume were observed with the novel strategy.

The economic, social and environmental benefits from using solar water heating in Zimbabwe was discussed by Batidzirai et al. [69], which could reduce coincident electricity winter peak demand by 13% and final energy demand by 27%, assuming a 50% penetration rate of solar heating potential demand. Up to 250 million dollars can be saved and CO_2 emissions can be reduced by 29% over the 25-year period.

The grey-box modelling approach based on fuzzy system to predict the outlet water temperature of the thermosyphon solar water heating system was employed by Kishor et al. [70]. The prediction performance results were compared with the neural network technique, and an improved prediction performance was observed with the fuzzy model.

The heat transfer model of all-glass vacuum tube collector used in forced-circulation solar water heating system was established by Li et al. [71] by considering the heat balance equation of water in single tube and manifold header. From this relationship and energy balance equation of collector, the collector outlet temperature and natural convection flow rate can be calculated. The validated experiments of this model were carried out in winter of Beijing, China.

The novel and affordable solar selective coating used in most ordinary solar water heating systems was developed by AlShamaileh [72]. The coating was fabricated by embedding a metallic particle composed of a nickel–aluminium (NiAl) alloy into the black paint. It was found that the new coating showed better performance compared to the untreated black paint by an average of 5 °C over a period of one year. Higher inhibition efficiency of corrosion was found for the alloy-containing paint compared to the untreated paint by more than 12%.

The novel solar water heating system based on loop heat pipe technology was proposed by Zhao et al. [73–75], which had the advantages of building-facade-integrated, low cost, highly efficient and aesthetically appealing, and could contribute to the reduction of fossil fuel consumption and carbon emissions associated with building's hot water production and supply.

The performance of a solar domestic hot water system consisting of a composite made of compressed expanded natural graphite (CENG) and phase change material (PCM) directly inside a flat plate solar collector was evaluated by Haillot et al. [76]. Several composites based on CENG and various storage materials (e.g., paraffin, stearic acid, sodium acetate trihydrate and pentaglycerin) were elaborated and characterised.

The statistically representative group of low-income residences equipped with a compact domestic solar water heater in Florianopolis, Brazil was monitored by Naspolini and Rüther [77] for one year. In comparison with identical residential units using electrical showerheads, the adoption of solar water heating could reduce the active, reactive and apparent power demands on the distribution utility of 49%, 29% and 49%, respectively.

The economic performance of residential rooftop solar water heating technology in the U.S was examined by Cassard et al. [78]. For a typical residential consumer, a system will reduce water heating energy demand by 50–85%, or a savings of 1600–2600 kWh per year, corresponding to an annual electric bill savings range of about 100 to over 300 dollars.

The improved differential control to the ordinary differential control operating with fixed switch-on and switch-off temperature differences was compared by Kicsiny and Farkas [79] in efficiency viewpoint, based on measured data of a particular system at Hungary and on a TRNSYS model developed for solar heating systems. The results revealed that the improved control provided a higher value of utilizability and brings forth fewer switches for the pumps.

The maximum-power point tracking control technology implemented using a microprocessor-based controller for solar heating system was developed by Huang et al. [80] to minimise the pumping power consumption at an optimal heat collection. The test results showed good tracking performance with small tracking errors. It was seen that the average mass flow rate for the specific test periods in five different days was between 18.1 and 22.9 kg/min with average pumping power between 77 and 140 W, which was greatly reduced as compared to the standard flow rate at 31 kg/min and pumping power 450 W based on the flow rate 0.02 kg/(s m^2) defined in the ANSI/ASHRAE 93-1986 Standard and the total collector area 25.9 m^2.

The level of the subsidy which Serbian government should offer in order to reach the level of solar water heating system deployment comparable to that of more developed countries was suggested by Stevanović and Pucar [81]. After financial analysis of the installation in six Serbian cities, followed by contingent valuation survey among household owners in Serbia, it was concluded that 20% subsidy was justified by CO_2 mitigation potential of the systems, while 50% subsidy, which lowered equity payback period to 5.5–6 years, generated most interest among household owners.

The thermal performance of a solar water heating system with heat pipe evacuated tube collector was analysed by Ayompe and Duffy [82] using data obtained from a field trial installation over a year in Dublin, Ireland. The maximum recorded collector outlet fluid temperature was 70.3 °C while the water temperature at the bottom of the hot water tank was 59.5 °C. The annual average daily energy collected was 20.4 MJ, energy delivered by the solar coil was 16.8 MJ, supply pipe loss was 3.6 MJ, solar fraction was 33.8%, collector efficiency was 63.2% and system efficiency was 52.0%.

The year-round energy performance of a domestic solar water heating system was predicted by Hazami et al. [83] based on evacuated tube collector recently commercialised in Tunisia by using a TRNSYS model validated through experimental tests under local weather conditions for 6 days spread over 2 months from November to July 2010. Results showed that for an annual total solar insolation of 5489.3 MJ/m^2, a total of 4653.13 MJ/m^2 was collected by the 3.4 m^2 collector with the average solar fraction of 84.4%. The annual average solar fraction of the flat-plate collector systems was less (68%) than that of the evacuated tube collector system (84%). An economic appraisal was compared to select the most cost-saving system.

The novel solar photovoltaic/loop-heat-pipe heat pump system was introduced by Zhang et al. [84,85] for hot water generation. Through conducting experiments, the electrical, thermal and overall efficiency of the module were around 10%, 40% and 50% respectively; whilst the system's overall performance coefficient was 8.7.

4.2. Analysis of the solar water heating technology

Works related to the solar water heating technology were found to be substantial, and the above case-to-case statements could be further analysed from the 6 aspects of performance characteristic and research methodology.

4.2.1. Integrated structure and individual components layout, sizing and optimisation

The reviewed works have been conducted to analyse the component characteristics of the solar water heating system, e.g., solar collector [56,63,71,76], coating surface of the collector [72], heat exchanger [51], control [79,80], and storage tank [48,56,63], and optimise the system integrated structure [25,48,56,63,67,68], which was helpful in determine the different configuration of the system and choose the most suitable one for applications in specific climate condition and geographic location.

4.2.2. Thermal performance simulation and prediction

Many theoretical works have been carried out to study the performance of the solar water heating technology and its associated heat and mass transfer processes. These works could be divided into the following two groups:

(1) Analytical models to address the heat transfer and thermal balance [51–53,55,57,68,70,71,73,74,84];
(2) Transient energy models to simulate the dynamic characteristics of the system [25,62,67,75,79,83,85].

In summary, the established theoretical models are sufficient to reveal the complex nature of the technology, optimise the system's configuration, suggest the favoured operating condition and predict its performance.

4.2.3. Laboratory based measurement compared against the modelling prediction

The aims of the experimental study [49,51–53,55,57,62,71,73–75,79,80,83–85] could be outlined as

(1) To identify the real performance of the system under the specified operating condition;
(2) to examine the reliability and accuracy of the established computer model; and
(3) to establish the correlation between the theoretical analysis and practical application.

In summary, the experimental or combined modelling and experimental works are significant and have been found to be in agreement with most theoretical results. These works also provide feasible approaches to manage the theoretical findings with regards to practical applications.

4.2.4. Dynamic performance evaluation through real time and onsite measurement

Evaluation to the dynamic performance of the system through real time and onsite measurement aimed to examine the prediction accuracy of the computer model established in the theoretical analysis to forecast the system's long-term performance in different climate and geographic conditions for the solar water heating system. The procedure and results were given by Tsilingiris [49], Lee and Sharma [61], Sanino and Reischel [62], García-Valladares [64], Ayompe and Duffy [82].

4.2.5. Performance assessment and social acceptance analyses

The benefits of the solar water heating system could fall into the energy-saving [54,58–60,69,77,78], cost-saving [50,54,57,59,68,69,75,78,81], and environment protection [54,55,64,69,81] aspects. The social recognition of the solar water heating system in different locations was investigated by Tsilingiris [49], Diakoulaki et al. [54], Batidzirai et al. [69], Naspolini and Rüther [77], Stevanović and Pucar [81], and Hazami et al. [83].

4.2.6. Dissemination, marketing and exploitation strategies

The marketing research of the solar water heating system was conducted by Furbo and Shah [57], Thür et al. [59], Purohit and Michaelowa [65] and Batidzirai et al. [69], and the policy and subsidy strategies including the local and international ones issued by the government to promote the system were also studied [65,69,78].

4.3. Conclusive remarks of the review works

In summary, the research works on solar water heating technology are substantial and focus on revealing the nature of the energy transfer occurring in the system, identifying the favoured system configuration and its associated components, optimising the structural/geometrical parameters of the system, suggesting the appropriate operating condition, building the bridge between theoretical analysis and experimental study, predicting the long-term system performance, analysing the impacts on society, economy and environment, and expanding the marketing application. All these efforts contribute to a target of creating an energy-efficient, cost-effective, structure-optimal and environmental-friendly solar water heating system.

5. Opportunities for further work

Although significant works have been conducted by now, there are still obvious opportunities to develop this technology.

5.1. Developing new, economically feasible and energy-efficient solar systems

The opportunity to develop new solar systems employing advanced technologies (e.g., loop heat pipe) or materials (e.g., phase change material) to replace conventional solar water heaters still remains open, which will create a new research area for the development of economically feasible and energy-efficient solar systems. The advantages of the systems still require further validation through theoretical and experimental studies. As well as this, the new solar systems in different configurations are still open to exploration.

5.2. Optimising the structural/geometrical parameters of the solar system configurations

Existing solar systems are technically and commercially mature and have no obvious chance to improve their performance. However, there are still opportunities for solar systems employing the advanced technologies or materials. For example, the low cost, flexible loop heat pipe with built-in capillary would be a favourite choice to replace the conventional parallel-laid heat pipe, and its performance improvement through the optimal study of the structural/geometrical parameters is still in the research stage. The main challenge is to find a method of overcoming the difficulties remaining in the existing solar systems, e.g., winter freezing, long-pipe water running and low efficiency.

5.3. Conducting the real time and onsite measurement

Laboratory-based testing could not imitate the actual system operation owing to the limitations of the laboratory conditions. Therefore, further tests may be carried out to evaluate the operational performance of the solar systems employing the advanced technologies or materials under real weather conditions. In addition, tests may also be performed under long-term schemes, i.e., seasonal or annual, to identify the real behaviour of the system. The testing results can be used to verify the annual operational performance data predicted by the computer model.

5.4. Assessing the energy, economic and environmental influences and social acceptance

In order to understand the potentials of the solar systems employing the advanced technologies or materials, the energy, economic and environmental influences and social acceptance should be analysed for the system under different climate conditions and geographic locations, which will help identify the most beneficial place for the promotion of the system. In addition, the energy-saving, carbon-emission-reduction and cost-saving index are the most expected figures for the government to issue the energy policy and subsidy programme, which play significant roles in guiding the marketing of the system.

5.5. Applying standardisation method to manufacture, choose and utilise the appropriate solar system

Standardisation is regarded as one of the most important works that needs to be studied in further, with the aim of integrating both structural and thermal performance parameters into the same documentation, helping the manufactures producing the standardised components and system installation, reducing the difficulties in seeking and determining the solar system to be used, and making convenience in managing the system for the customers.

5.6. Exploring policy and subsidy strategies for the market expansion of the solar system

Solar heating is a cost-effective technology that could avoid the dependence on the gradual disappearance of the fossil fuels, and alleviate the international social, environmental and economical pressures of the energy import and export. Therefore, the policy and subsidy programme for the development of the technology should be encouraged. In addition, the exploitation of the solar markets could bring a large amount of benefits, including the development of the national economy, increase of the employment rate, and promotion of the industry related to the solar technology (e.g., steel, iron, and glass manufacturing).

6. Conclusion

A critical review towards the solar water heating technology has been carried out. This work was dedicated to address a number of important issues, namely, (1) theory relating to the system; (2) types of the system; (3) associated parametric data relating to the system; (4) current and future market potentials of the system and their building application profiles; (5) research questions that have been undertaken and to be undertaken; and (6) future development opportunities in relation to the technology. The results of this work help in identifying the current status, potential problems in existence; and future directions in relation to research, development and practical application of the technologies in buildings, and thus helps in promoting development of this building integrated renewable energy technology. It will therefore contribute to achieving the China and international targets for energy saving, renewable energy utilisation, as well as carbon emission reduction in building sector.

Solar water heating is the technology converting solar energy to usable heat for applications in hot water. The working principle of the solar water heating system was described, as well as its classifications into passive and active systems, direct and indirect systems or based on the configurations of the solar collectors. The mathematical analytical equations for the determination of the heat output and system efficiency were presented for the solar system with a collector, heat exchanger or tank.

Over the past few decades, the global solar market has grown rapidly owing to the low cost of the solar systems under certain conditions, financial incentives, regulatory instruments, education and environmental and local visual impacts. However, there still exist various barriers to the promotion of solar technology, which

could be summarised into technical, economic and other (legal, cultural and behavioural) barriers.

The practical applications of the solar water heaters in a building's roofs and envelopes were illustrated. The building balcony/façade integrated solar systems overcame the barriers of the conventional roof-mounted and roof-integrated solar water heaters and presented with advanced features, e.g., the improved architectural appearance and reduced construction cost of the building. However, the winter freezing and long water piping problems still limited the prevalence of this system.

Research works relating to the solar water heating systems are numerous but the major points lie in (1) whole structure and individual components layout, sizing and optimisation; (2) thermal performance simulation and prediction; (3) laboratory based measurement compared against the modelling prediction; (4) dynamic performance evaluation through real time and on-site measurement; (5) energy saving, economic and environmental performance assessment, and social acceptance analyses; and (6) dissemination, marketing and exploitation strategies.

In view of the current status and outstanding problems, the further development opportunities are outlined as (1) developing new, economically feasible and energy-efficient solar systems employing advanced technologies or materials; (2) optimising the structural/geometrical parameters of the solar system configurations to enhance the energy performance; (3) conducting the real time and onsite measurement under real weather conditions and long-term schemes; (4) assessing the energy, economic and environmental influences and social acceptance under different climate conditions and geographic locations; (5) applying standardisation method to manufacture, choose and utilise the appropriate solar system; and (6) exploring policy and subsidy strategies for the expansion of the domestic and international markets of the solar system.

Acknowledgement

This work was financially supported by the Guangdong Natural Science Foundation, China (S2013010011674), Science and Technology Innovation Project of Education Department of Guangdong Province (2013KJCX0061), Science Research Project of Science and Information Technology Bureau of Guangzhou (2014J4100200), State Key Laboratory of Subtropical Building Science of South China University of Technology (2015ZB19), and Doctoral Foundation Project of Guangdong University of Technology (12ZK0380).

References

[1] BP. Energy — consumption by fuel, 1965–2008 (XLS). Statistical review of world energy 2009; 31st July 2006 [retrieved 24.10.09].
[2] Enerdata Publication. Global energy review. Enerdata Publication; 2009.
[3] Peak uncertainty, when will we run out of fossil fuels. [Online]. Available: ⟨http://www.science20.com/absentminded_professor/peak_uncertainty_when_will_we_run_out_fossil_fuels-70294⟩; 2011 [accessed 27.09.11].
[4] National Academy of Sciences, National Academy of Engineering, Institute of Medicine, National Research Council. Understanding and responding to climate change, 2008 Edition. National Academies Reports; 2008.
[5] European Solar Thermal Technology Platform (ESTTP). Solar heating and cooling for a sustainable energy future in Europe (Revised). [Online]. Available: ⟨http://www.estif.org/fileadmin/estif/content/projects/downloads/ESTTP_SRA_Revised Version.pdf⟩; 2009 [accessed 27.09.11].
[6] European Solar Thermal Industry Federation (ESTIF). Solar thermal action plan for Europe: heating & cooling from the Sun. EU: European Solar Thermal Industry Federation (ESTIF); 2007.
[7] Boyle G. Renewable energy: power for a sustainable future. second ed. UK: Oxford University Press; 2004.
[8] Zhai X, Wang R, Dai Y, Wu J, Ma Q. Experience on integration of solar thermal technologies with green buildings. Renew Energy 2008;33:1904–10.
[9] Zhai X, Wang R. Experience on solar heating and cooling in China. Renew Sustain Energy Rev 2008;12:1110–28.
[10] Jaehnig D, Isaksson C. Solar integration: five easy ways to incorporate solar thermal into conventional heating systems. Renew Energy World 2006;6:66–72.
[11] Yoshikawa M. Solar heat collector system. United States patent No. 4901537; Date of Patent: 20th February 1990.
[12] Hestnes A. Building integration of solar energy systems. Sol Energy 1999;67:181–7.
[13] Dunn P, Reay D. The heat pipes. Phys Technol 1973;4:187–201.
[14] Reay D, Kew P. Heat pipe. fifth ed. UK: Elsevier; 2006.
[15] Solar water heating system. [Online]. Available: ⟨http://www.solardirect.com/swh/swh.htm⟩; 2011 [accessed 27.09.11].
[16] Hastings S, Wall M. Sustainable solar housing, vol. 2. Exemplary buildings and technology. Earthscan; 2007, UK.
[17] Ogueke N, Anyanwu E, Ekechukwu O. A review of solar water heating systems. J Renew Sustain Energy 2009;1:1–21.
[18] Nahar N. Capital cost and economic viability of thermosyphonic solar water heaters manufactured from alternate materials in India. Renew Energy 2002;26:623–35.
[19] Khalifa A. Forced versus natural circulation solar water heaters: a comparative performance study. Renew Energy 1998;14:77–82.
[20] Comparison – tubes vs. plate. [Online]. Available: ⟨http://www.nrg-solar.co.uk/index.php?option=com_content&task=view&id=144&Ite⟩; 2011 [accessed 14.06.11].
[21] Struckmann F Analysis of a flat-plate solar collector, 2008 MVK160 Heat and Mass Transport, Project Report. Lund, Sweden; 8th May 2008.
[22] Duffie J, Beckman W. Solar engineering of thermal processes. UK: John Wiley & Sons; 1980.
[23] Kalogirou S. Solar thermal collectors and applications. Prog Energy Combust Sci 2004;30:231–95.
[24] U.S. Department of Energy. Siting your solar water heating system. [Online]. Available: ⟨http://energy.gov/energysaver/articles/siting-your-solar-water-heating-system⟩; 2012 [accessed 20.07.14].
[25] Hobbi A, Siddiqui K. Optimal design of a forced circulation solar water heating system for a residential unit in cold climate using TRNSYS. Sol Energy 2009;83:700–14.
[26] U.S. Department of Energy. Solar water heating system maintenance and repair. [Online]. Available: ⟨ttp://energy.gov/energysaver/articles/siting-your-solar-water-heating-system⟩; 2012 [accessed 20.07.14].
[27] Philibert C. Barriers to technology diffusion: the case of solar thermal technologies. Organisation for Economic Cooperation and Development/International Energy Agency. UK: OECD/IEA; 2006.
[28] Weiss W, Mauthner F. Solar heat worldwide: markets and contribution to the energy supply 2009. 2011 ed.. UK: IEA Solar Heating & Cooling Programme; 2011.
[29] Weiss W, Bergmann I, Stelzer R. Solar heat worldwide: markets and contribution to the energy supply 2007. 2009 ed.. UK: IEA Solar Heating & Cooling Programme; 2009.
[30] IEA. World energy outlook 2008. OECD/IEA; 2008.
[31] IEA. Renewables for heating and cooling. OECD/IEA; 2007.
[32] Weiss W, Biermayr P. Potential of solar thermal in Europe. ESTIF, EU; 2009.
[33] Rantil M Solar heating – kilowatts or megawatts. Presented at the REWP Technology & Policy Seminar. IEA, Paris, France; 5th April 2006.
[34] IEA. Renewable energy – market and policy trends in IEA countries. UK: OECD/IEA; 2004.
[35] Renewable energy policy network for the 21st century (REN21). Renewables 2010. Global Status Report; 2010.
[36] Sun in action II – a solar thermal strategy for Europe. Market overview, perspectives and strategy for growth, vol. 1. UK: ESTIF; 2003.
[37] IEA. Renewables information 2005. OECD/IEA; 2005.
[38] Karen F, Neumann K. Removing barriers to solar energy use in Santa Barbara county. Santa Barbara, CA: Community Environmental Council; 2004.
[39] Voss K. Solar energy in building renovation – results and experience of international demonstration buildings. Energy Build 2000;32:291–302.
[40] IEA-SHC Task 28/ECBCS Annex 38: sustainable solar housing. ISIS demonstration housing project in Freiburg, Germany. [Online]. Available: ⟨http://www.iea-shc.org/task28/publications/index.html⟩; 2011 [accessed 19.05.11].
[41] IEA-SHC Task 28/ECBCS Annex 38: sustainable solar housing. House W – demonstration house in the Czech Republic. [Online]. Available: ⟨http://www.iea-shc.org/task28/publications/index.html⟩; 2011 [accessed 19.05.11].
[42] IEA-SHC Task 28/ECBCS Annex 38: sustainable solar housing. Plus energy house in Thening, Austria. [Online]. Available: ⟨http://www.iea-shc.org/task28/publications/index.html⟩; 2011 [accessed 19.05.11].
[43] IEA-SHC Task 28/ECBCS Annex 38: sustainable solar housing. Sunny woods, Zurich, Switzerland. [Online]. Available: ⟨http://www.iea-shc.org/task28/publications/index.html⟩; 2011 [accessed 19.05.11].
[44] Weiss W, Stadler I. Facade integration – a new and promising opportunity for thermal solar collectors. IEA-SHC Task 26, industry workshop; 2nd April 2001.
[45] New type solar water heater. [Online]. Available: ⟨http://www.me.ntu.edu.tw/~nec/en/en_e_03.htm⟩; 2011 [accessed 22.09.11].
[46] Butler D., Ku F., Swanson T. Loop heat pipes and capillary pumped loops – an applications perspective. Space Technology and Applications International Forum – STAIF; 2002, UK.
[47] Ritidech S, Donmaung A, Kumsombut K. Experimental study of the performance of a circular tube solar collector with closed-loop oscillating heat-pipe with check valve (CLOHP/CV). Renew Energy 2009;34:2234–8.
[48] Kaygusuz K. Experimental and theoretical investigation of latent heat storage for water based solar heating system. Energy Convers Manag 1995;36:315–23.

[49] Tsilingiris P. Design, analysis and performance of low-cost plastic film large solar water heating systems. Sol Energy 1997;60:245–56.
[50] Mohsen M, Akash B. Evaluation of domestic solar water heating system in Jordan using analytic hierarchy process. Energy Convers Manag 1997;38:1815–22.
[51] Morrison G, Nasr A, Behnia M, Rosengarten G. Analysis of horizontal mantle heat exchanger in solar water heating systems. Sol Energy 1998;64:19–31.
[52] Kalogirou S, Panteliou S, Dentsoras A. Modeling of solar domestic water heating systems using artificial neural networks. Sol Energy 1999;65:335–42.
[53] Kalogirou S, Panteliou S. Thermosiphon solar domestic water heating systems: long-term performance prediction using artificial neural networks. Sol Energy 2000;69:163–74.
[54] Diakoulaki D, Zervos A, Sarafidis J, Mirasgedis S. Cost benefit analysis for solar water heating system. Energy Convers Manag 2001;42:1727–39.
[55] Mather D, Hollands K, Wright J. Single- and multi-tank energy storage for solar heating systems: fundamentals. Sol Energy 2002;73:3–13.
[56] Mills D, Morrison G. Optimisation of minimum backup solar water heating system. Sol Energy 2003;74:505–11.
[57] Furbo S, Shah L. Thermal advantages for solar heating systems with a glass cover with antireflection surfaces. Sol. Energy 2003;74:513–23.
[58] Kablan M. Forecasting the demand on solar water heating systems and their energy savings potential during the period 2001–2005 in Jordan. Energy Convers Manag 2003;44:2027–36.
[59] Thür A, Furbo S, Shah L. Energy savings for solar heating systems. Sol Energy 2006;80:1463–74.
[60] Pillai I, Banerjee R. Methodology for estimation of potential for solar water heating in a target area. Sol Energy 2007;81:162–72.
[61] Lee D, Sharma A. Thermal performances of the active and passive water heating systems based on annual operation. Sol Energy 2007;81:207–15.
[62] Sanino L, Reischel R. Modelling and identification of solar energy water heating system incorporating nonlinearities. Sol Energy 2007;81:570–80.
[63] Kulkarni G, Kedare S, Bandyopadhyay S. Determination of design space and optimisation of solar water heating systems. Sol Energy 2007;81:958–68.
[64] García-Valladares O, Pilatowsky I, Ruíz V. Outdoor test method to determine the thermal behaviour of solar domestic water heating systems. Sol Energy 2008;82:613–22.
[65] Purohit P, Michaelowa A. CDM potential of solar water heating systems in India. Sol Energy 2008;82:799–811.
[66] Roulleau T, Lloyd C. International policy issues regarding solar water heating, with a focus on New Zealand. Energy Policy 2008;36:1843–57.
[67] Raffenel Y, Fabrizio E, Virgone J, Blanco E, Filippi M. Integrated solar heating systems: from initial sizing procedure to dynamic simulation. Sol Energy 2009;83:657–63.
[68] Kulkarni G, Kedare S, Bandyopadhyay S. Optimisation of solar water heating systems through water replenishment. Energy Convers Manag 2009;50:837–46.
[69] Batidzirai B, Lysen E, Egmond van S, Sark van W. Potential for solar water heating in Zimbabwe. Renew and Sustain Energy Rev 2009;13:567–82.
[70] Kishor N, Das M, Narain A, Ranjan V. Fuzzy model representation of thermosyphon solar water heating system. Sol Energy 2010;84:945–55.
[71] Li Z, Chen C, Luo H, Zhang Y, Xue Y. All-glass vacuum tube collector heat transfer model used in forced-circulation solar water heating system. Sol Energy 2010;84:1413–21.
[72] AlShamaileh E. Testing of a new solar coating for solar water heating applications. Sol Energy 2010;84:1637–43.
[73] Zhao X, Wang Z, Tang Q. Theoretical investigation of the performance of a novel loop heat pipe solar water heating system for use in Beijing, China. Appl Therm Eng 2010;30:2526–36.
[74] Wang Z, Zhao X. Analytical study of the heat transfer limits of a novel loop heat pipe system. Int J Energy Res 2011;35:404–14.
[75] Wang Z, Duan Z, Zhao X, Chen M. Dynamic performance of a facade-based solar loop heat pipe water heating system. Sol Energy 2012;86:1632–47.
[76] Haillot D, Goetz V, Py X, Benabdelkarim M. High performance storage composite for the enhancement of solar domestic hot water systems, Part I: storage material investigation. Sol Energy 2011;85:1021–7.
[77] Naspolini H, Rüther R. The impacts of solar water heating in low-income households on the distribution utility's active, reactive and apparent power demands. Sol Energy 2011;85:2023–32.
[78] Cassard H, Denholm P, Ong S. Technical and economic performance of residential solar water heating in the United States. Renew Sustain Energy Rev 2011;15:3789–800.
[79] Kicsiny R, Farkas I. Improved differential control for solar heating systems. Sol Energy 2012;86:3489–98.
[80] Huang B, Ton W, Wu C, Ko H, Chang H, Yen R, Wang J. Maximum-power-point tracking control of solar heating system. Sol Energy 2012;86:3278–87.
[81] Stevanović S, Pucar M. Financial measures Serbia should offer for solar water heating systems. Energy Build 2012;54:519–26.
[82] Ayompe L, Duffy A. Thermal performance analysis of a solar water heating system with heat pipe evacuated tube collector using data from a field trial. Sol Energy 2013;90:17–28.
[83] Hazami M, Kooli S, Naili N, Farhat A. Long-term performances prediction of an evacuated tube solar water heating system used for single-family households under typical Nord-African climate (Tunisia). Sol Energy 2013;94:283–98.
[84] Zhang X, Zhao X, Xu J, Yu X. Characterization of a solar photovoltaic/loop-heat-pipe heat pump water heating system. Appl Energy 2013;102:1229–45.
[85] Zhang X, Zhao X, Shen J, Hu X, Liu X, Xu J. Design, fabrication and experimental study of a solar photovoltaic/loop-heat-pipe based heat pump system. Sol Energy 2013;97:551–68.